Analysis of Factors Affecting the Occurrence and Severity of Air Traffic Control Operational Errors

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7,302 words

Abstract The rate of occurrence of air traffic control operational errors are recognized as an important measure of the safety performance of the National Airspace System. As the volume of air traffic increases and new automated air traffic control decision support tools are introduced, there is a concern not only to increase the level of safety in the system by reducing the occurrence of operational errors but to ensure that efforts to increase the capacity of the system do not adversely affect safety. The paper presents an analysis of recent trends in air traffic control operational errors in the United States, discusses the factors that have been found to influence the rate of occurrence of these errors, and examines the relationship between the severity of operational errors in an en-route environment and the traffic characteristics at the time. The paper describes the limitations of the information currently available to support the analysis of operational errors and concludes by addressing the data requirements for future research to better understand the causal factors affecting the rate of occurrence of operational errors and to develop strategies to enhance the safety of the National Airspace System.

INTRODUCTION

A central component of the current efforts of Federal Aviation Administration (FAA) to modernize the U.S. National Airspace System (NAS) and to accommodate growing levels of air traffic is the progressive implementation of new or expanded air traffic control procedures and their associated automated decision support systems. At the same time, the FAA has identified a mission goal to enhance safety levels within the NAS (*1*). One aspect of this is the number of operational errors that occur, where an operational error is defined as: *An occurrence attributable to an element of the air traffic control system in which: (1) Less than the applicable separation minima between two or more aircraft, or between an aircraft and terrain or obstacles (e.g., operations below minimum vectoring altitude (MVA); equipment/personnel on runways), as required by FAA Order 7110.65 or other national directive; or (2) An aircraft lands or departs on a runway closed to aircraft operations after receiving air traffic authorization.* (*2*)

Thus the rate at which operational errors occur in the NAS comprises one of the measures of performance of the air traffic control system (*1*). However, in recent years, the operational error rate in Air Route Traffic Control Centers has shown a steady increase, rather than a decrease (*2*). Therefore it is of obvious concern that the fielding of new air traffic control automated decision support tools designed to increase the ability of the NAS to handle the increasing volumes of air traffic with greater efficiency does not have the unintended effect of further increasing operational errors, and ideally helps to reduce the likelihood of such errors. Fortunately, operational errors do not occur very often. However, this also means that determining the factors behind any change in the underlying rate with any degree of statistical confidence is a significant challenge.

The FAA performs an investigation of each operational error, and maintains a database of the resulting reports. There have also been a number of prior research studies into the causal factors involved in operational errors. These studies have been summarized by Rodgers *et al.* (*3*) in a study that also examined the sector characteristics associated with 85 operational errors at the Atlanta Center between June 1992 and June 1995. These studies have generally found, perhaps not surprisingly, that air traffic complexity appears to be a major factor in the occurrence of operational errors. Rodgers *et al.* found that a factor analysis of sixteen complexity factor variables indicated three primary underlying dimensions: traffic activity, sector size, and military operations. The apparent role of air traffic complexity in the occurrence of operational errors suggests that if one effect of the implementation of automated decision support tools is to increase the complexity of the air traffic situation that controllers are handling, this can be expected to result in an increase in operational errors, other things being equal.

Of course, other things are not necessarily equal, and the implementation of such tools may not increase those aspects of air traffic complexity that are most relevant to the occurrence of operational errors. Indeed, these tools may in fact allow controllers to manage an increased volume of air traffic in a way that reduces the likelihood of operational errors being made, or alerts controllers in a timely way to a developing conflict so that it can be resolved before there is a loss of separation. Thus a better understanding of the causal factors involved in operational errors will assist in the implementation of automated decision support tools in a way that minimizes the risk of increasing operational errors.

This paper presents an analysis of recent trends in air traffic control operational errors in the United States, discusses the factors that have been found to influence the rate of occurrence of these errors, and examines the relationship between the severity of operational errors in an en-route environment and the traffic characteristics at the time.

RECENT TRENDS IN OPERATIONAL ERROR RATES

Not surprisingly, there tend to be more operational errors at busier facilities, whether simply due to the greater number of opportunities for operational errors to occur as a result of the higher level of traffic or because the busier facilities tend also to have more complex traffic patterns. Therefore, it is usual to express the rate of occurrence of operational errors in terms of the volume of air traffic handled at the facility. Across all facilities in 1999, there were 1.41 operational errors per 100,000 operations at Air Route Traffic Control Centers (ARTCCs) and 0.65 operational errors per 100,000 operations at stand-alone Terminal Radar Approach Control (TRACON) facilities (*2*). The recent trend in these error rates is shown in Figure 1. While the TRACON operational error rate has declined slightly over the past five years, the rate across all ARTCCs has increased significantly from 1997 to 2000.

The variation in the error rate in the past two years compared to the activity level at all 21 ARTCCs is shown in Figure 2. The figure suggests that although there is a high degree of variability across facilities, not only does the *number* of operational errors tend to be higher at the busier facilities, but the operational error *rate* also tends to be higher at the busier facilities. The 1999 operational error rate for Anchorage Center (ZAN) is significantly higher than would be expected from the trend shown by the other Centers, although this did not occur in 2000. Figure 2 also shows a second order polynomial trend line fitted to the data for each year. This suggests that the number of operational errors increases at a somewhat faster rate than the square of the traffic. The figure also suggests that the trend line has shifted upward slightly in 2000 compared to 1999.

The corresponding data on the number of operational errors and activity at the 23 stand-alone TRACONs are shown in Figure 3. Because the relatively low number of errors at the less busy TRACONs results in a large variation in the operational error *rate* from year to year, the figure plots the number of errors rather than the rate. However, a second order polynomial trend line fitted to the data for each year shows that the operational error rate appears to increase somewhat with activity, although the effect is not particularly strong. There does not appear to be much difference between the trend lines for 1999 and 2000, which is consistent with the average rate for both years shown in Figure 1.

These findings have important implications for future trends in the number of operational errors as traffic levels rise, unless ways can be found to reduce the operational error rate at a given traffic level. The large amount of scatter in the data not only results in a fairly poor statistical fit to the data, but suggests that there are a number of facility-specific factors that play a significant role in the operational error rate.

PREVIOUS RESEARCH INTO FACTORS AFFECTING OPERATIONAL ERROR RATES

Because of the obvious risk posed to the safety of air traffic by operational errors, their causal factors have been subject to extensive study for many years. Schroeder and Nye (*4*) examined various measures of workload conditions that existed at the time operational errors and deviations occurred, using data from the operational error reports. They found that while fairly strong correlation existed between several of the five causal factor categories used in the reports, the correlation between the occurrence of any of the causal factor categories and the reported traffic complexity or the number of aircraft in the sector was much weaker. Rodgers and Nye (*5*) classified operational errors into three levels of severity and examined how the number of aircraft being worked, traffic complexity, aircraft flight profile, and causal factors involved in the error varied across the different levels of severity. They did not find significant differences in the error severity with the number of aircraft or traffic complexity. They did find that some causal factors and flight profiles were associated with a higher percentage of more severe errors.

Isaac and Ruitenberg (*6*) discuss a wide range of issues associated with human performance in air traffic control. The authors indicate that for a homogenous air traffic control environment, 70 to 74 percent of operational errors typically occur under light to moderate traffic conditions and complexity, while 45 percent of errors occur during a controller's first 15 minutes on the position and 62 percent of errors are made by controllers who have had less than six years experience.

Sector Characteristics

A study by Mogford *et al.* (*7*) investigated factors involved with the en-route sector complexity and the effects of those elements on controller decision-making, and identified 16 air traffic control complexity factors. They found that two of these factors, requirement for longitudinal sequencing and spacing and frequency congestion, could be combined in an equation to adequately account for the overall sector complexity, although using all of the factors improved the prediction of sector complexity.

Rodgers *et al.* (*3*) attempted to isolate the air traffic control complexity factors that create conditions for operational errors using data from the Atlanta Center. It was found that three possible underlying dimensions (traffic activity, sector size, and whether special use (*i.e.* military) airspace was involved) could be used to describe the airspace. A high number of operational errors occurred at an altitude of 29,000 feet (Flight Level 290), the altitude at which the vertical separation standards change. The mean traffic volume was found to be higher at the time of the error than in a 1995 review of sector density. Sectors were divided into no-error, low-error and high-error categories based on the rate of occurrence of operational errors. Significant differences between the no-error and high-error sectors were found for four sector characteristics: frequency of problematic weather, radio frequency congestion, total complexity (obtained by summing 15 variables adopted from Mogford *et al.*), and average complexity (using data from the 1995 facility review). Additionally, high-error sectors were found to have more aircraft, were more complex, and exhibited higher controller workload than no-error and low-errors sectors.

Situation Awareness

Operational errors occur because controllers allow an air traffic situation to evolve in which they either fail to recognize that two aircraft are about to lose separation or they become aware of this too late to be able to take action in time to prevent the loss of separation. Thus in general the occurrence of operational errors is associated with some failure of situation awareness on the part of the controller.

Endsley & Rodgers (*8*) examined air traffic controllers' situation awareness and workload in a passive air traffic control (ATC) environment and the implications for the occurrence of operational errors. During the study, controllers viewed the recreation of an operational error. At various times during each experiment, the screen was blanked and the controllers were asked to indicate the location of all known aircraft and several characteristics of the airplanes in question (*e.g.* their altitude, heading, and ground speed). Significant deficiencies in the ongoing situational awareness of the subjects were found in this study. Subjects had a fairly low ability to report the existence of many aircraft, or accurately recall their location and many of their parameters. Their accuracy was significantly impacted by the number of aircraft present in the scenario and to a lesser extent by the perceived workload.

Durso *et al.* (*9*) attempted to find a way to predict performance of en-route air traffic controllers from their situation awareness and perceived workload. The NASA Task Load Index (*10*) was used to assess several dimensions of controller workload. It was found that if controllers viewed a task as mentally demanding, they also viewed the task as physically demanding, temporally demanding, effortful, and relatively frustrating. Overall, the study showed that the Task Load Index provides information on two important components: workload and subjective performance.

Controller Workload and Dynamic Density

Many definitions and models have been developed to attempt to measure air traffic controller workload (*11*). Stein (*12*) created a simulation experiment to determine the relationship between a number of airspace factors and controller workload. The study demonstrated a strong relationship between controller workload and a subset of airspace and traffic-related variables, including the clustering of aircraft in a small amount of sector airspace, number of handoffs outbound, total number of flights handled, and the number of hand-offs inbound. Bruce (*13*) attempted to identify specific factors in the present ATC system that affect workload and controller performance. This study found generally significant linkages between controller workload and traffic volume, level of traffic complexity, and the allocation of the air traffic control sector duties. The complexity of the traffic configuration was found to have the most significant effect on controller performance.

Recently there have been a growing interest in developing ways to combine the various factors that affect controller workload into a single measure, termed dynamic density. Laudeman *et al*. (*14*) created a model to explain the factors involved with dynamic density. They developed a metric that predicts controller workload as a function of multiple air traffic characteristics in a volume of airspace.

ANALYSIS OF THE SEVERITY OF OPERATIONAL ERRORS

Not all operational errors pose the same risk of a collision. In some cases aircraft barely avoid a collision and in others they are several miles apart at their closest point. Therefore it seems appropriate to classify operations errors by some measure of severity and focus attention on those that pose the greatest risk of collision. The FAA has recently begun to do this, and has defined an operational error severity index, that takes account of a number of factors, including the minimum separation, the closing speed of the two aircraft, and whether the aircraft flight crews received conflict resolution advisories from the Traffic Alert and Collision Avoidance System on their aircraft. However, these severity index values are only available for operational errors that have occurred since January 2001, when the procedures to determine the index were finalized.

In order to explore both the distribution of severity of operational errors and how this is affected by traffic conditions in the sector at the time, an analysis was undertaken of data for operational errors occurring at the following seven Air Route Traffic Control Centers during the three-year period from January 1997 to December 1999:

- Atlanta (ZTL)
- Chicago (ZAU)
- Cleveland (ZOB)
- Indianapolis (ZID)
- Kansas City (ZKC)
- Memphis (ZME)
- Washington (ZDC)

These seven ARTCCs comprise a contiguous area of airspace that covers some of the most congested airspace in the United States. In 1999, these seven Centers handled 42 percent of the traffic at the 20 ARTCCs covering the continental United States (CONUS) and accounted for 56 percent of the operational errors at the CONUS Centers. During the three-year period, the seven Centers experienced a total of 816 operational errors. The number of errors in each Center varied from about 60 in Kansas City and Memphis Centers to about 160 in Washington Center. Detailed data on each operational error are recorded in an operational error report that is filed following the investigation of the error by the FAA. For each of these errors, the data contained in the operational error report were obtained from the FAA.

Definition of Operational Error Severity

The operational error severity index recently adopted by the FAA requires access to detailed data about the aircraft flight paths and radio communications between the controller and aircraft involved that are not available in the operational error reports. Therefore the analysis described in this paper adopted a simpler definition of operational error severity based only on the minimum separation between the two aircraft involved. The cumulative distribution of the minimum horizontal separation that occurred during the error is shown in Figure 4. About 10 percent of the errors had a minimum horizontal separation of less than 2 nautical miles (nm), and only about 2 percent had a minimum horizontal separation of under 1 nm. About 30 percent of the errors had a minimum horizontal separation of 4 nm or greater (*i.e.* within 20 percent of the minimum separation standard).

However, for a loss of safe separation to occur, the aircraft have to lose *both* horizontal *and* vertical separation. For operational errors at altitudes of flight level (FL) 290 and below, about 8 percent reported zero minimum vertical separation and about 45 percent reported a minimum vertical separation less than 500 feet, while about 10 percent reported a minimum vertical separation of 800 feet or greater (*i.e.* within 20 percent of the minimum vertical separation standard for FL 290 and below). For operational errors at altitudes above FL 290, about 7 percent reported zero minimum vertical separation and about 16 percent reported a minimum vertical separation less than 500 feet, while about 20 percent reported a minimum vertical separation of 1,600 feet or greater (*i.e.* within 20 percent of the minimum vertical separation standard above FL 290).

This analysis shows that only a very small proportion of operational errors involved any significant risk of a collision. Therefore it was decided to define the operational error severity in terms of the closest proximity both horizontally and vertically. The FAA defines a Near Mid-Air Collision (NMAC) as less than 500 feet separation between aircraft. The FAA has also recently announced that a loss of separation of no more than 20 percent of the minimum separation standard will be viewed as a technical violation and treated differently from errors with greater loss of separation in terms of assessing controller performance. These errors can viewed as procedural, in the sense that while the minimum separation standard was violated, no great hazard existed. In the absence of any established criteria for intermediate cases, the terms and definitions shown in Table 1 were adopted for the analysis in the current study. Errors classified as NMACs were determined based on the minimum separation given in the operational error report, not on whether the flight crew filed an NMAC report.

The distribution of operational errors using this definition of severity is shown in Figure 5. Only 0.6 percent of the operational errors were considered critical and only a further 21 percent were considered serious. Over 40 percent were procedural. The larger number of operational errors classified as NMACs compared to those classified as critical is surprising. However, of the 14 errors in the sample classified as NMACs on the basis of the reported minimum separation, pilots filed NMAC reports in only three cases. In 9 cases the operation error report gave the slant separation as zero. Therefore it is possible that for several of these cases values of zero were entered for the minimum separation when in fact the actual minimum separation could not be determined or was uncertain, suggesting that the proportion of NMAC errors may be overestimated. Whether cases incorrectly classified as NMACs were in fact critical errors or a less severe category cannot be determined from the data.

Controller Workload and Traffic Complexity

The operational error reports provide information on both the number of aircraft being handled by the controller at the time of the error, as well as an assessment of the traffic complexity using a five-point scale (5 being the highest complexity). Analysis of the reports showed that about 50 percent of the errors occurred with fewer than nine aircraft in the sector and about 80 percent of the errors occurred with fewer the 12 aircraft in the sector. However, without knowing the typical distribution of traffic in each sector, it is hard to say whether this represents a lighter or heavier than usual traffic volume. Not surprisingly, as the number of aircraft in the sector increases, a larger proportion of the errors occurred at higher levels of traffic complexity. The operational error reports note whether the number of aircraft in the sector contributed to the traffic complexity. Also not surprisingly, as the number of aircraft increased or the traffic complexity increased, the percentage of occurrences where the number of aircraft contributed to the traffic complexity also increased.

The number of aircraft was not the only factor that contributed to traffic complexity, although it was the most important. Controller experience was reported to be a significant factor at intermediate levels of traffic complexity, while weather, airspace, and flow control factors were reported to play a role at higher levels of traffic complexity. Although controller workload is influenced by many factors, it appeared from the data that the measure of traffic complexity used in the reports is highly correlated with those factors. Figure 6 shows the proportions of operational errors in each category of error severity for different levels of traffic complexity. The most severe errors appear to occur at moderately high levels of traffic complexity, but not at either very high or very low levels. Procedural errors appear to be a fairly constant proportion at all levels of traffic complexity. These results do not suggest that the more serious operation errors are a result of high levels of controller workload or traffic complexity, but occur at all levels of workload and complexity.

Situational Awareness

The operational error reports provide information on whether the controller was aware of the error developing. Analysis of the reports found that the proportion of errors in which the controller was aware of the error developing did not appear to vary to significantly with either the number of aircraft in the sector or the traffic complexity. The controllers' awareness of the error developing appears to have increased slightly at higher levels of traffic, while the proportion of errors in which the controller was aware of the error appears to be somewhat lower at intermediate levels of complexity. The small increase in awareness with the number of aircraft could be due to the greater vigilance needed to handle higher traffic volumes or the fact that traffic flow tends to be more structured at higher traffic volumes. There may also be an effect of staffing decisions, with the more experienced controllers working the busier, more complex sectors.

Figure 7 shows the proportion of errors in which the controller was aware of the error developing for different classes of error severity. The proportion of controllers recognizing the situation as it developed declined with increasing severity of the outcome (or more likely the more severe outcomes were associated with a higher proportion of situations in which the controller was not aware of the situation developing). The small increase for the most severe category may be due to the small number of cases or the questionable number of NMAC cases discussed above. Significantly, in only about 20 percent of the serious, critical and NMAC errors was the controller found to be aware of the situation developing. This suggests that automated decision support tools that improve the controller situation awareness and alert controllers to developing situations that could involve a loss of separation could significantly reduce the occurrence of the more serious operational errors.

REQUIREMENTS FOR FUTURE RESEARCH

Previous studies have demonstrated the importance of both the number of aircraft in the sector and the complexity of the traffic pattern on controller situation awareness and workload, and in turn the correlation between these factors and the occurrence of operational errors. In order to be able to better understand how these two effects influence the occurrence of operational errors, it is necessary to have access to detailed data on traffic volume and complexity at a sectors level throughout the NAS (or at least for those facilities being studied). Unfortunately, this information is not routinely available at present. While detailed data is recorded at each facility, it is usually only preserved for 15 days in case it is needed to investigate an incident and then is discarded.

Establishing a database of the variation of sector traffic levels and complexity over time would address a fundamental limitation of the operational error reports. While these reports provide information on the traffic levels and complexity at the time each error occurs, they provide no information on how often these conditions arise but no errors occur. Such a database would enable the changes in traffic levels and complexity between the baseline and implementation periods to be analyzed, and any changes in the relative frequency of occurrence of the traffic conditions that prevail at the time of any operational errors to be identified. However, for such a database to be useful, it will be necessary to define a number of relatively high level performance metrics that can be extracted from the detailed aircraft flight path data and expressed on a sector basis for discrete time intervals. This will permit the variation in these metrics over time to be determined for a given sector, as well as the value of the metrics in the relevant sectors at the time of each error.

CONCLUSIONS

The analysis of operational errors presented in this paper suggests that only a relatively small proportion of all operational errors involve a close encounter between aircraft. In the great majority of cases, although required separation had been lost, there was no significant risk of a collision. Only 2.3 percent of all operational errors in seven ARTCCs over a three-year period involved a near mid-air collision or a critical operational error (defined as a minimum separation less than 1 nm horizontally and 500 feet vertically). This has significant implications for the reporting of operational errors. If the errors of concern are those where a significant risk of a collision existed, and these are only a small proportion of all errors, the change in the number of these errors is much more important than the change in the total number. Indeed, the serious errors could easily be increasing while the total number of errors go down. Therefore meaningful reporting of the number of operational errors needs to include some measure of the severity of the errors in question.

In the course of the current study it became clear that the existing sources of data that are routinely available are inadequate to fully understand the way in which traffic conditions in a specific air traffic control facility influence the number of operational errors or to anticipate the likely effect of introducing new air traffic control automated decision support tools. Therefore efforts need to be undertaken on two fronts. First, processes need to be put in place to record and archive the necessary data and to make appropriate measures of the traffic conditions in each sector over time available for subsequent analysis. In addition, detailed data on the use of the various automation tools also need to be available, in order to be able to determine which tools were in use during the period leading up to an error occurring, as well as to be able to compare this situation with other times when errors did not occur. Second, further research will be needed to better understand how to make effective use of these data once they are available.

ACKNOWLEDGEMENTS

This paper is based on research undertaken for the Federal Aviation Administration by the National Center of Excellence for Aviation Operations Research with support from the FAA Free Flight Phase 1 Program Office. The author wishes to acknowledge the assistance of staff from the Free Flight Phase 1 Program Office, FAA Air Traffic Services, and the National Aviation Safety Data Analysis Center in providing access to the necessary data and information, and suggestions for the conduct of the research. Helpful information was also provided during the course of the research by staff from the MITRE Center for Advanced Aviation System Development and Oak Ridge National Laboratory.

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LIST OF TABLES AND FIGURES

TABLE 1 Classification of Operational Error Severity

Severity Classification	Criteria
Near Mid Air Collision (NMAC)	Less than 500 feet slant separation
Critical	500 feet or more slant separation Horizontal separation less than 1 nm *and* vertical separation less than 500 feet
Serious	Horizontal separation of less than 1 nm *and* vertical separation of at least 500 feet but less than 800 feet (FL 290 and below) or 1,600 feet (above FL 290) *or* Horizontal separation of at least 1 nm and less than 4 nm *and* vertical separation less than 500 feet
Intermediate	Horizontal separation of at least 1 nm and less than 4 nm *and* vertical separation of at least 500 feet but less than 800 feet (FL 290 and below) or 1,600 feet (above FL 290)
Procedural	Horizontal separation of 4 nm or more *and* vertical separation of 800 feet or more (FL 290 and below) or 1,600 feet or more (above FL 290)

FIGURE 1 Operational Error Rate

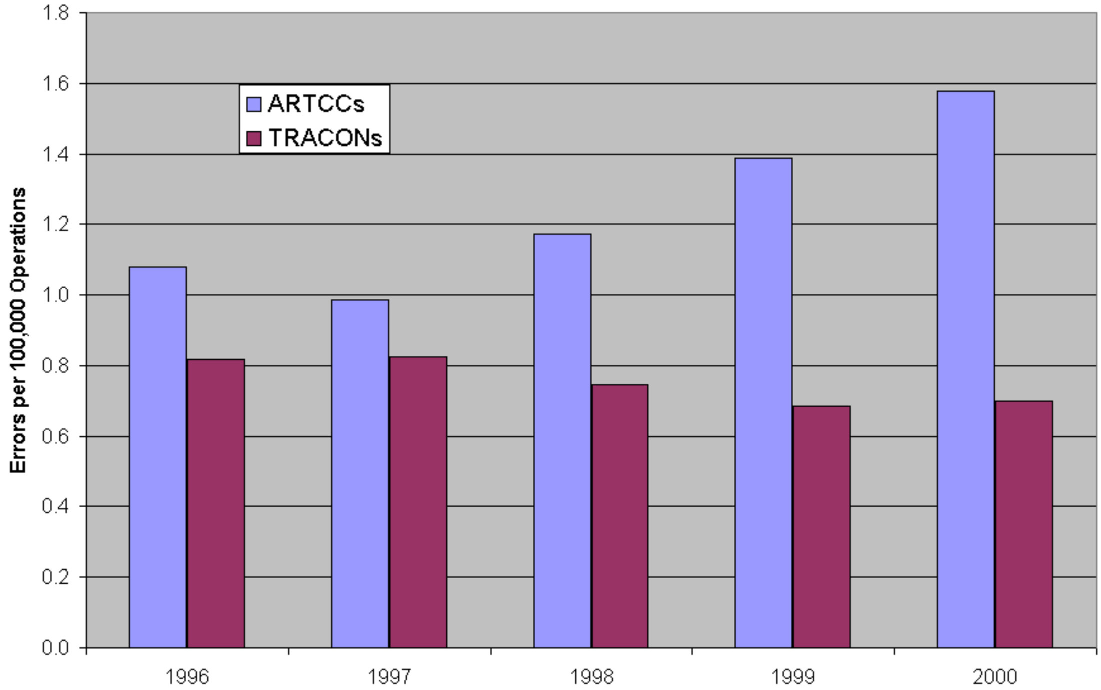

FIGURE 2 ARTCC Operational Error Rate – Calendar Year 1999 and 2000

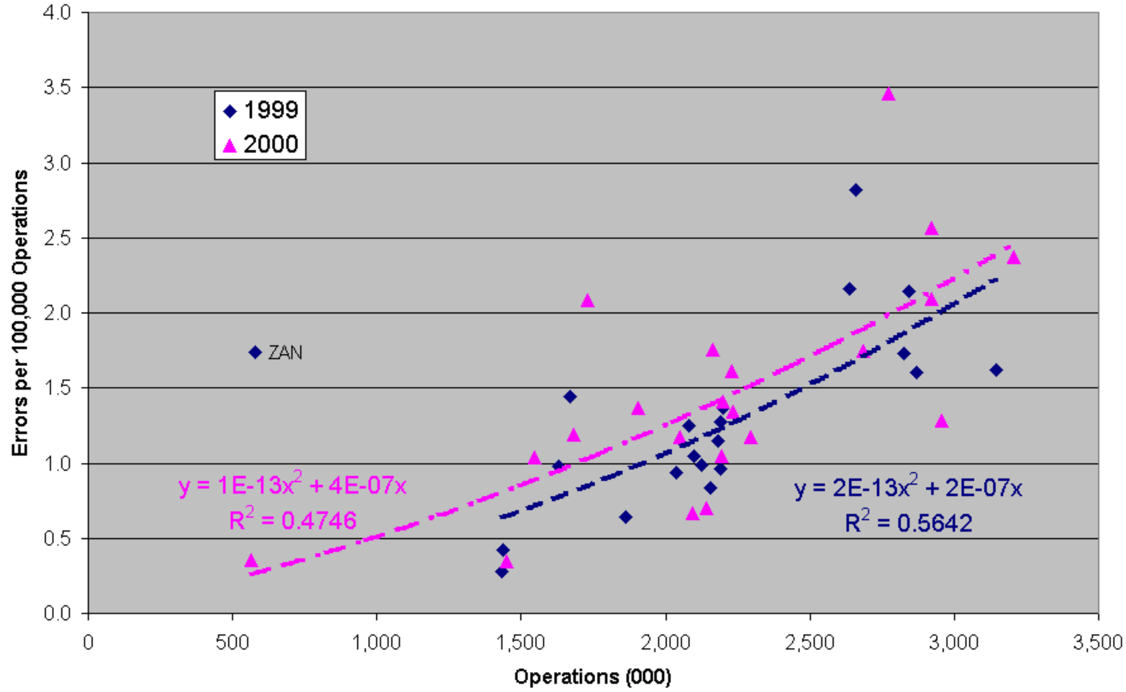

FIGURE 3 TRACON Operational Errors – Calendar Year 1999 and 2000

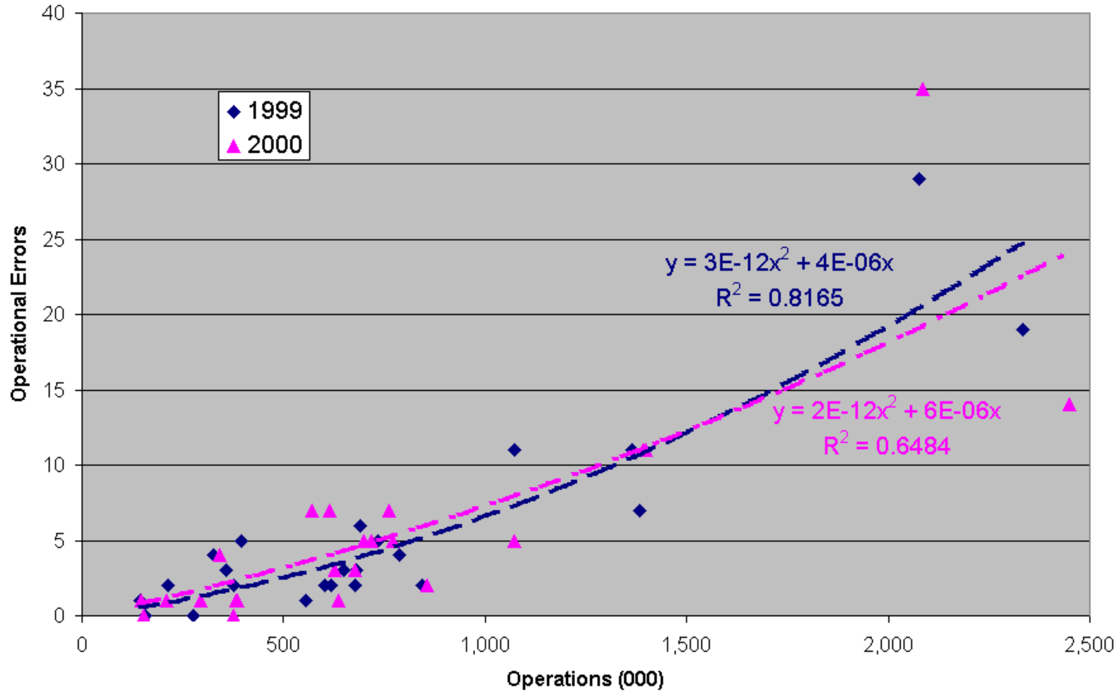

FIGURE 4 Cumulative Distribution of Minimum Horizontal Separation

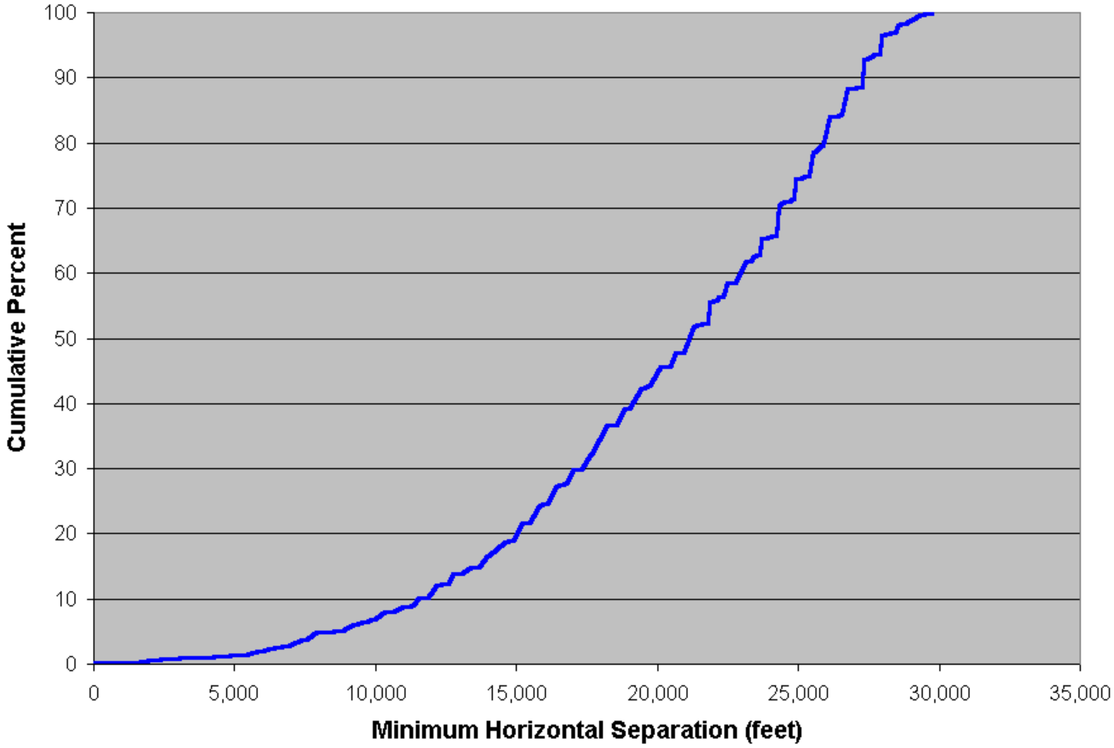

FIGURE 5 Distribution of Operational Errors by Severity

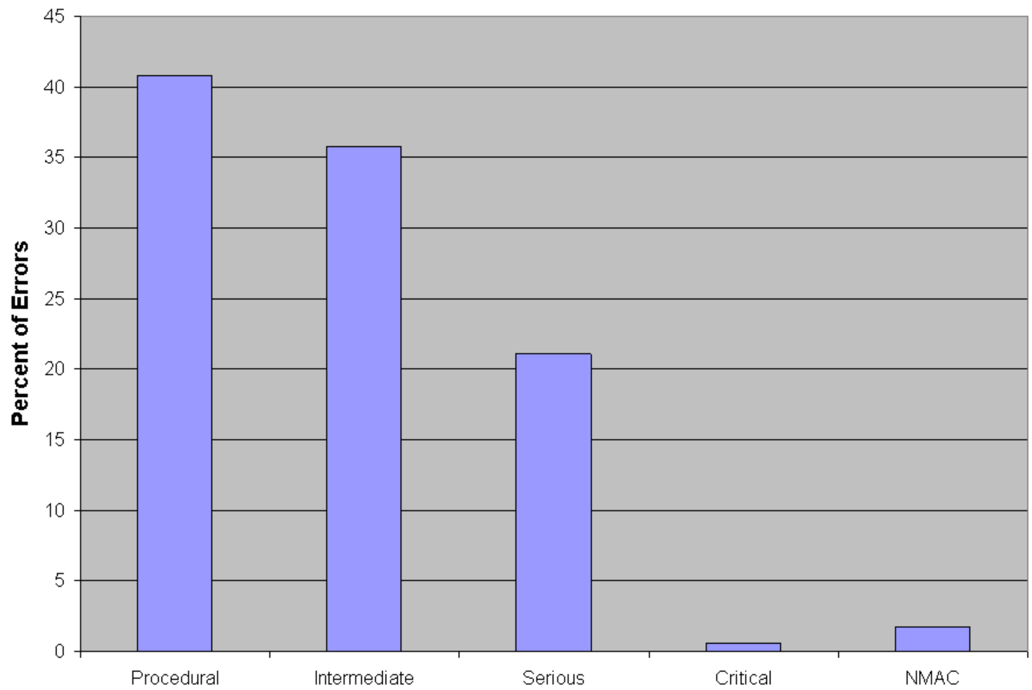

FIGURE 6 Severity of Errors at Different Levels of Traffic Complexity

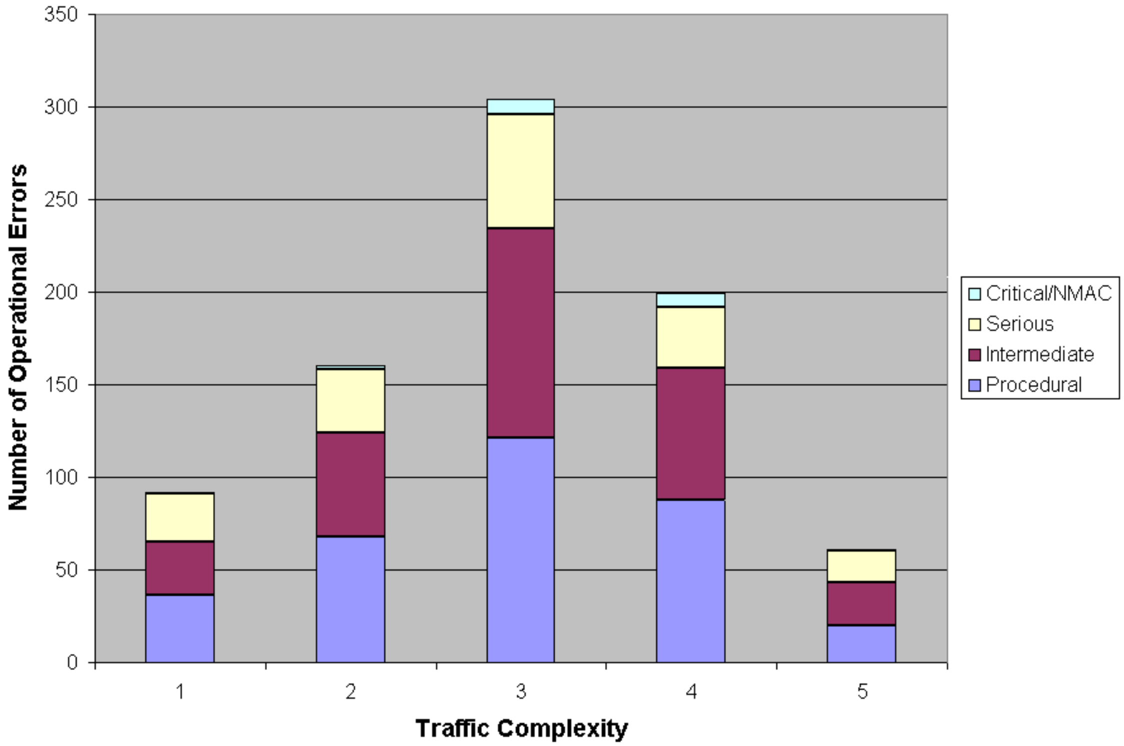

FIGURE 7 Controller Awareness of Errors of Varying Severity